HEAVY ION PHYSICS

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Abstract
A collision of two lead nuclei at ultrarelativistic energies will produce a tiny droplet of quark-gluon plasma, which expands, cools, converts via a phase transition to a hadron gas, which decouples and sends hadrons to detectors. Theoretical and experimental expectations concerning these quite novel phenomena are reviewed.

1. INTRODUCTION

Particle physics has usually progressed along the energy axis: higher energies cross thresholds and reveal new phenomena. At present the most important issue is to cross the possible production thresholds of the Higgs or of supersymmetric particles. There is another axis one can also think of: the radius of the colliding object. As we in the nature only have nuclei with atomic numbers A varying between 1 and 238, this is a very short axis, only from the proton radius of about 1 fm to the Uranium radius of about 7 fm. However, moving along it may nevertheless reveal qualitatively new phenomena: one moves from particle physics to condensed elementary particle matter physics. Concretely, since the colliding objects are nuclei, the type of matter one can hope to produce is QCD matter in its different phases: hadron matter or quark-gluon plasma.

This lecture will briefly review concepts and activities in this field concentrating on the following topics:

- Perspective: Physics with p+p (e+p, e+e) vs. A+A collisions or Elementary Particle Physics vs. Condensed Elementary Particle Matter Physics
- Numbers, scales, ways of thinking about A+A (Pb+Pb)
- An average event, signals of quark-gluon plasma
- One solid result computable from the action of QCD: the equation of state
- Simulating cosmology in the laboratory?

A good reference to the topic is the series of the Proceedings of Quark Matter meetings [1].

The basis of the entire field is its experimental program, which essentially is as summarised in Table 1.

Accelerator	$p_{\rm lab}$	$\sqrt{s}$	Δy
AGS/Brookhaven	10 GeV/c	5 GeV	3
SPS/CERN Pb+Pb (proposed)	40 GeV/c	9 GeV	4.5
SPS/CERN Pb+Pb	160 GeV/c	17 GeV	6
RHIC/Brookhaven, April 1999-		200 GeV	11
LHC-ALICE/CERN, 2005(?)-		5500 GeV	17

Table 1: Existing and forthcoming A+A facilities, $\Delta y \equiv y_{\rm beam} - y_{\rm target}$.

The size of the population of physicists actively engaged in this field is > 1000 – the attendance of the 1995 Quark Matter meeting was 550. One might also estimate that about 50% of both personnel and materials resources are "nuclear physics" resources.

2. COMPARING PHYSICS IN p+p AND $A + A$ COLLISIONS

The goal of particle physics is to determine the laws of particle physics (= fields, symmetries, form of action, values of parameters) using accelerator experiments. In experiments at p+p colliders, the protons in p+p are sources of constituents $(q, \bar{q}, g)$ the interactions of which one wants to study:

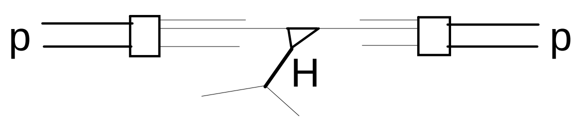

Figure 1: A p+p collision with Higgs production.

Here two gluons from colliding protons collide and produce a Higgs via a top quark loop – if there is sufficient energy. Due to the large Higgs mass, the process is extremely local, both in space and in time, via the uncertainty principle. Similarly, the cross section is extremely small. The produced Higgs particle does not care of the fragments of the protons and gets out of the interaction region unmodified. Or more precisely: further interactions correspond to perturbative corrections of higher order.

In a heavy ion collision the nucleons in A+A are also sources of constituents the *coherent, collective* interactions one wants to study. Since the goal is to create a collectively interacting system, one wants to produce as many quanta as possible, no very large scale is involved, and the cross section is large (Fig. 2).

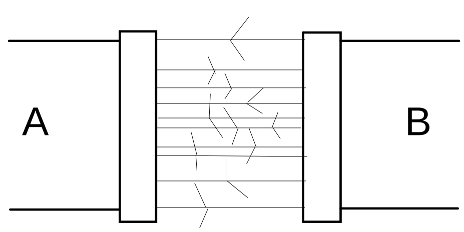

Figure 2: An A+A collision with quark-gluon plasma formation.

Symbolically, we here have two colliding nuclei, pictured at extremely high energies (LHC or TeV energies) as two clouds of quarks and gluons. When the clouds pass each other, some of the pointlike constituents interact with each other. Due to the size of the system there are many interactions, many quarks and gluons are formed. This system formed is nothing but *quark-gluon plasma*. It is first unthermalised, but – possibly – thermalises due to reinteractions of the produced quarks and gluons. It expands, cools, converts to *hadron gas* via a phase transition, expands further as hadron gas which finally decouples to free hadrons, which then fly to the detectors. We shall presently put numbers into this scenario. It is the standard expectation, and the whole point of the heavy ion program is to convert it from a scenario to a description of facts of nature.

There is another way of putting the distinction between p+p and $A+A$ physics: it is the distinction of particle physics vs. condensed particle matter physics.

The laws of **particle physics**: Lagrangian, fields, symmetries, parameters, are determined with p+p (e+p, e+e) collisions. We have **known** theories, QCD:

$$L_{\rm QCD} = \frac{1}{4}F^a_{\mu\nu}F^a_{\mu\nu} + \sum_i \bar{\psi}_i[D(A)+m_i]\psi_i$$

or the MSM (Minimal Standard Model with its 20 parameters out of which $\gtrsim$1 are still unknown (Higgs mass, precise values of some mixings). The main problem is to search for **new** theories. A prototype candidate is the Minimal Supersymmetric Standard Model with its 125 parameters. At large energy scales these theories are weak coupling ones and precise predictions for a given set of parameters can be computed.

In **condensed particle matter physics** one takes a known Lagrangian, and applies it to an extended system. For $L_{\rm QCD}$ these systems are

- $A+A$ collision, size 10^{-14} m,
- Universe at $ct \approx 10^4$ m,
- Quark star, size 10^4 m, A=10^{57}.

The relevant energy scales are 10 MeV ... few GeV and this is thus dominantly nonperturbative physics, no precise predictions for Pb+Pb can be made, no definite single signal for quark-gluon plasma can be formulated. One needs phenomenology, effective theories, physical thinking – or intensive number crunching for the equation of state!

There is one crucial difference between usual condensed matter physics and condensed particle matter physics. In the former one has a minimum distance scale a, the size of atoms, built in the problem and thus only the thermodynamic limit $V \to \infty$ is needed. In the latter also the continuum limit $a \to 0$ has to be taken and this brings with it qualitatively new phenomena in quantum theory – like anomalies.

One typical example of a phenomenological suggestion [2] which is plausible but which nobody at the moment can verify from first principles, is the existence of strangelets (stable uds systems, which would appear as hadrons of anomalously small charge/mass, $Z/A \ll 1/2$). As this caused some discussion during the school, I will sketch the argument here. It is somewhat akin to the fact that an nnnn state is more unstable than an nnpp state, in spite of the Coulomb repulsion between protons, because only two neutrons can be put to the lowest $l=0$ state. Neglect quark masses, assume they form an ideal $T=0$ Fermi gas, impose electrical neutrality (a very large system has to be $\approx$ neutral) and compute the energy per quark for udd- and uds-systems at the same pressure. The distribution function of an ideal $T = 0$ Fermi gas is (μ = chemical potential = Fermi energy)

$$n(p) = \frac{g}{2\pi^2}\theta(\mu - p), \tag{1}$$

so that

$$n = \frac{g}{6\pi^2}\mu^3, \quad p = \frac{g}{24\pi^2}\mu^4 = \frac{1}{3}\epsilon, \quad E_q = \frac{\epsilon}{n} = \frac{3}{4}\mu, \tag{2}$$

where for one quark flavour $g = 2 \cdot 3 = 6$. For a udd-system electrical neutrality or $n_d = 2n_u$ implies that $\mu_d = 2^{1/3}\mu_u \equiv 2^{1/3}\mu$. Here one has the effect of the Fermi principle: since there are more d quarks they have to go to higher momentum states. Averaging over u and d quarks then gives

$$E_q(\text{udd}) = \frac{1}{4}(1 + 2^{1/3} + 2^{1/3})\mu. \tag{3}$$

For a uds-system all quarks have the same chemical potential $\tilde{\mu}$ and

$$E_q(\text{uds}) = \frac{1}{4}(1 + 1 + 1)\tilde{\mu}. \tag{4}$$

We want to compare the systems in equilibrium, at the same pressure:

$$p(\text{udd}) = \frac{\mu^4}{4\pi^2}(1 + 2^{4/3}) = p(\text{uds}) = \frac{\tilde{\mu}^4}{4\pi^2}3 \tag{5}$$

so that

$$\frac{E_q(\text{uds})}{E_q(\text{udd})} = \left(\frac{3}{1 + 2^{4/3}}\right)^{3/4} = 0.89. \tag{6}$$

A quark in a uds system thus seems to be more strongly bound than in usual nuclear matter, which is a udd-system, i.e., the ground state of nuclear matter would actually have the uds-quark content. A large literature and several experiments have evolved on the basis of this simple and suggestive idea. The point here is that, although we know L_{QCD}, we are totally unable to carry out the first-principle computations required to state whether it is true or not; phenomenological analyses and experiments are required.

Experiments are only possible for L_{QCD}, theories relevant for higher energies can be tested with cosmological observations. One of the most striking cosmological applications here is the derivation of $(B - \bar{B})/S$ = net baryon number/entropy of the universe from L_{MSM} or from beyond-the-standard model theories.

3. NUMBERS, WAYS OF THINKING ABOUT $A + A$

Let us now try to put some numbers to the scenario initiated by Fig.2. What are the sizes, lifetimes, temperatures expected?

First, for a spherical nucleus (some are cigar-shaped!) the density is

$$n_A(r) = \frac{n_0}{1 + e^{(r - R_A)/d}}, \quad \int d^3x\, n_A(r) = A,$$

where the nuclear radius is $R_A = 1.18A^{1/3} - 0.45$ fm $= 6.5$ fm for Pb (A=208 = 82+126) $\gg d = 0.54$ fm. The interior density thus is fairly constant and from normalisation to A equal to $n_0 = 0.17/\text{fm}^3$ = nuclear matter density. The crucial variable here is the nuclear radius R_A; we would hope it to be $\gg 1/\Lambda_{\rm QCD} \approx 1$ fm, but unfortunately $\gg$ here is at best a factor six.

To treat nuclear geometry in reactions, one usually defines the thickness function:

$$T_A(b) = \int_{-\infty}^{\infty} dz\, n_A(\sqrt{b^2+z^2})$$

and the overlap function:

$$T_{AB}(b) = \int d^2b_1 d^2b_2 \delta^2(b-b_1-b_2) T_A(b_1) T_B(b_2),$$

normalised as

$$\int d^2b\, T_{AB}(b) = AB, \qquad T_{AA}(0) \approx \frac{A^2}{\pi R_A^2} \sim \frac{A^{4/3}}{10\,\mathrm{mb}}.$$

In practice: if σ is the cross section of a process on the pp level, the number of those processes in an A+A collision at impact parameter b is

$$\sigma T_{AA}(b).$$

In the laboratory frame, in which the nucleus is moving with the gamma factor γ = energy/mass = $E_A/M_A = AE/Am_N = E_{\rm beam}/m_N$ the nucleus appears as Lorentz contracted:

$$\begin{aligned} \gamma &= 10 \qquad && \text{SPS}, \\ &= 100 && \text{RHIC}, \\ &= 2750 && \text{LHC}. \end{aligned} \tag{7}$$

Note, however, that the nucleus has to be pictured as also having slowly moving components and for those the γ factor is correspondingly less.

3.1 The system at $t = 0.1$ fm after the collision at LHC

Initially one thus has the two nuclei contracted into thin pancakes approaching each other along the z axis. The nuclei are collections of gluons and quarks with, in first approximation (g_N is inferred from [3]),

$$g_A(x,Q^2) = A g_N(x,Q^2). \tag{8}$$

Since one knows the parton-parton cross sections, one can compute [4, 5, 6] how many gluons, quarks and antiquarks are produced in an average collision in a certain rapidity interval, $-0.5 < y < 0.5$, say. Futhermore, to be able to do the computation in perturbation theory and to meaningfully count the number one must involve a large energy scale by demanding that the produced partons have large transverse momentum, $p_T > p_0 = 2$ GeV, say. This magnitude is actually determined by a requirement of "saturation"[4, 6]. One finds at LHC energies, $\sqrt{s} = 2750 + 2750$ GeV, that there in an average central Pb+Pb collision appear

$$4350 \text{ gluons} \quad + \quad 200 \text{ quarks} \quad + \quad 190 \text{ antiquarks}, \tag{9}$$

which carry a transverse energy of

$$12950\,\text{GeV for gluons} \quad + \quad 620\,\text{GeV for quarks} \quad + \quad 590\,\text{GeV for antiquarks.} \tag{10}$$

This is Fig.2 in quantitative form. Although definite numbers are given here, they should rather be taken as an illustrative scenario.

How do we picture the above result in space-time? Here one simply uses the uncertainly principle: the above quanta are formed at a time $1/p_0 = 0.1$ fm/c after the collision. Thus they are in the volume

$$R_{\text{Pb}} = 6.54 \text{ fm}, \quad \pi R_{\text{Pb}}^2 = 134 \text{ fm}^2 \Rightarrow V_i = \pi R_{\text{Pb}}^2/p_0 = 13.4 \text{ fm}^3, \tag{11}$$

and the corresponding number and energy densities are

$$n_g = \frac{325}{\text{fm}^3}, \quad n_q = \frac{14.9}{\text{fm}^3}, \quad n_{\bar{q}} = \frac{14.2}{\text{fm}^3}, \tag{12}$$

$$\epsilon_g = 967\frac{\text{GeV}}{\text{fm}^3}, \quad \epsilon_q = 46.2\frac{\text{GeV}}{\text{fm}^3}, \quad \epsilon_{\bar{q}} = 44.0\frac{\text{GeV}}{\text{fm}^3}. \tag{13}$$

3.2 Thermalisation, expansion, cooling

Now we – in this scenario – have a collection of a large number of gluons and quarks in a limited volume of space-time. This is nothing but quark-gluon plasma, although so far no statement has been made about thermalisation. Actually, at LHC energies the gluonic part of the system is very close to thermalisation already at formation [6]. To the extent that

$$\text{mean free path} \ll R_A \tag{14}$$

further collisions will thermalise the system. It then expands and cools. The expansion has two components, longitudinal and transverse. The interior expands first only longitudinally, while from the sides the system leaks outwards tranversally. The information of this outward leak is communicated to the interior at the velocity of sound and the maximal duration of longitudinal expansion thus is

$$R_A/v_{\text{sound}} \approx \sqrt{3}R_A \approx 10\,\text{fm}. \tag{15}$$

Beyond that time the expansion becomes 3-dimensional and has to be treated numerically. At some stage the system has cooled to T_c and begins to convert into the hadron phase via a phase transition. After the phase transition the system may still expand in the hadron gas phase, until it ultimately decouples and the hadrons fly to the detectors. During the previous hotter stages the system has also emitted various weakly interacting particles which also will be seen in the detectors.

To represent this scenario one often draws the diagram in Fig. 3. In this one has built in the additional important assumption that the evolution only depends on the proper time $\tau = \sqrt{t^2 - z^2}$, $z =$ longitudinal coordinate. Then, at some fixed and late time t, the system at $z = 0$ may already be cooled down while the fast forward or backward moving parts are still, due to time dilatation, very hot.

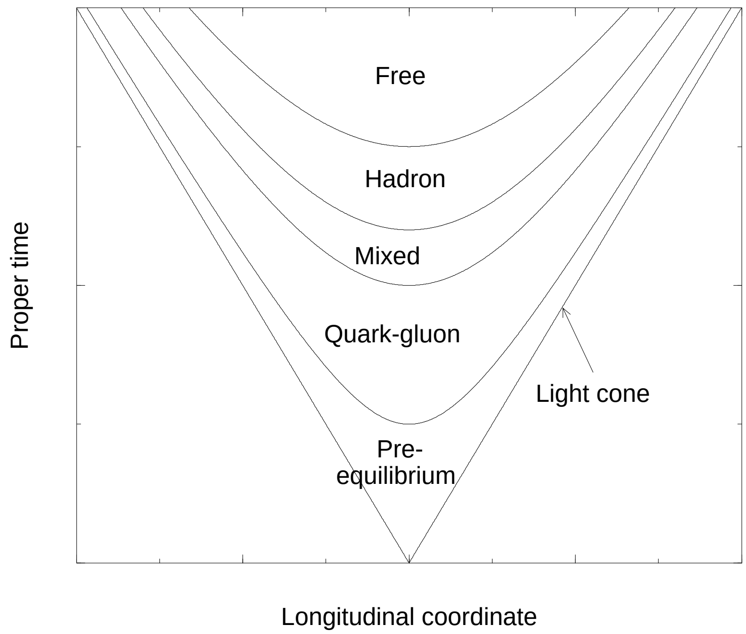

Figure 3: A space-time picture of an A+A collision

One should again warn that this is a scenario, hypothesis. It is fully developed only at LHC energies. At present SPS energies it seems that one has just passed T_c in part of the system. The whole point of the experimental heavy ion program is to convert any scenario to a series of physical facts and at the same time uncover totally new phenomena in particle physics.

To make the thermal aspects of the scenario somewhat more quantitative, let us take a massless boson-fermion gas with

$$p = p(T) = aT^4, \quad s = \text{entropy density} = p'(T) = 4aT^4, \tag{16}$$

$$\epsilon = \text{energy density} = Ts - p = 3aT^4, \tag{17}$$

or

$$\begin{aligned} \epsilon = 3p = \frac{g}{2} \cdot \frac{\pi^2}{15} T^4 &= \frac{g}{2} \cdot 85.6 \Big(\frac{T}{\text{GeV}}\Big)^4 \frac{\text{GeV}}{\text{fm}^3}, \\ n = \text{number density} = \frac{g}{2} \cdot \frac{2\zeta(3)}{15} T^3 &= \frac{g}{2} \cdot 31.7 \Big(\frac{T}{\text{GeV}}\Big)^3 \frac{1}{\text{fm}^3}, \\ g = g_B + \frac{7}{8} g_{F+\bar{F}}, &\quad (\frac{7}{8} \to \frac{3}{4} \text{ in } n), \end{aligned} \tag{18}$$

and assume that the system corresponding to the gluonic energy density ($g_B = 16$) in eq.(13) is thermalised. One finds consistently with eq.(18) that $T_i = 1.10$ GeV. This is a huge temperature.

If the system is thermalised, its further evolution is described by adiabatic or entropy conserving equations. This implies that the total entropy $S = sV$ and net baryon number $B - \bar{B}$ in a comoving volume V are constant. To define the comoving volume include only longitudinal expansion and take the simplest possible flow, the Bjorken similarity flow, with

$$s(t, z) = s(\tau) = 4aT^3(\tau), \qquad v(t, z) = \frac{z}{t} \equiv \tanh\theta, \tag{19}$$

for which the comoving $V = \pi R_A^2 \tau \Delta\theta$, i.e., depends on the θ interval considered. Identifying average particle motion with the flow, this is just the rapidity interval of observed particles. Since for massless bosons $s = 3.60n$, then from eq.(9) the initial entropy (for $-0.5 < y < 0.5$) is about 15000. The power of adiabatic equations is that this is constant. If no entropy is generated until the end, this is also the final entropy. If the final hadron gas is massless, as is almost the case for pions, the final pion ($\pi^{\pm,0}$) multiplicity would then be approximately the same as that of the initial gluons, i.e., about 4000. Entropy generation during the expansion can only increase this number. Analoguous statements hold for the other conserved quantity, the net baryon number $B - \bar{B}$. Initially from eq.(9) it is about 3, thus also the final observed baryon-to-entropy ratio would be about 3/15000.

There are many factors which might change in the scenario outlined above. Shadowing (violations of eq.(8)) and higher order corrections might change the initial numbers, entropy generation and 3d expansion effects might be significant, the kinetics of the phase transition are unknown. But this large number of uncertainties just means that the stage is set for new discoveries.

In this context it is also important to keep in mind why precisely one can expect the discovery potential to rapidly increase from SPS to RHIC to LHC. The reason is that at higher energies events can be expected to be more perturbative, "jetty", because

- of the small x increase of structure functions, observed to be unexpectedly rapid by HERA at DESY [3]
- at fixed jet scale (take $p_T = 2$ GeV, which is marginally perturbative) smaller x-values are reached at larger $\sqrt{s}$

The relevant x values are, for $p_0 = 2$ GeV,

$$\begin{aligned} x &\sim \frac{2}{10} = 0.2 \quad \text{SPS}, \\ &\sim \frac{2}{100} = 0.02 \quad \text{RHIC}, \\ &\sim \frac{2}{2750} \approx 0.001 \quad \text{LHC}. \end{aligned}$$

4. AVERAGE EVENT, SIGNALS

As discussed earlier, the study of quark matter in heavy ion collisions is dominantly large cross section physics, though also some hard signals with somewhat suppressed cross sections are important. It is thus important to have an idea of an average central (head-on, zero impact parameter) collision. A typical measurement result at energies available at present is shown in Fig.4. Extrapolating and estimating, Table 2 gives a rough composition of the debris from which the existence, space-time history and properties of quark-gluon plasma are to be inferred.

The goal thus is to measure in each event the type and momentum of each particle (the total number is ~ 10000 at LHC). This number is so large that much physics can actually be done on an event-by-event basis.

The main types of signals are as follows:

Hadronic signals test final stages of the expanding system, since the hadrons decouple from the hadron gas at some $T_{\text{decoupling}} < T_c$. One complicating factor always is the effect of resonances: pions dominantly come from decays of the rather heavy ρ, which on the other hand was formed as the "last collision" of the expanding hadron gas. The obvious questions to be answered are now whether the hadron relative abundances are in agreement with thermal equilibrium in hadron gas and whether there is evidence for flow. How does the possible flow depend on $\sqrt{s}$ and on A? Are there any anomalous enchancements in strange particle ratios?

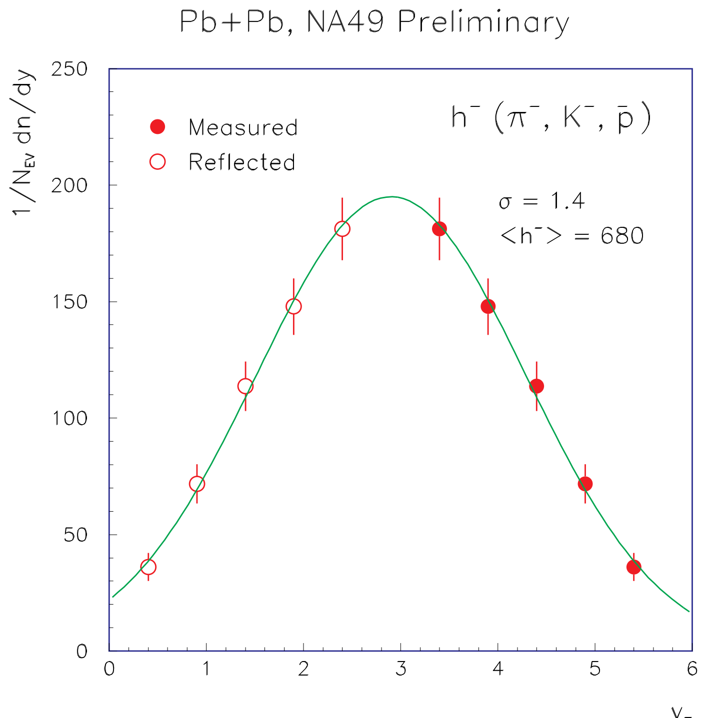

Figure 4: The rapidity distribution of negative particles in Pb+Pb measured (for $y > 3$) by the NA49 experiment at the CERN SPS at $\sqrt{s}$=17 GeV.

particle	$\sqrt{s}$=17	$\sqrt{s}$=5500	phenomenon
π^+	**200**	1000	Flow, $T_{\text{decoupling}}$,
π^-	**200**	1000	hadron gas, system size,
γ	>400	>2000	interferometry
p	**35**		Stopping, n_B
$e^\pm$	2	10	Thermal emission
K_s^0	**27**	200	Strangeness
Λ	14	20	enhancement
$\bar{p}$		70	
$\rho,\omega \to e^+e^-$	0.01	0.05	ρ,ω in matter
J/ψ	$\mathbf{10}^{-4}$	10^{-2}	Spectral lines
Υ	10^{-9}	10^{-4}	in matter
$c\bar{c}$		30	Backgrounds to
$b\bar{b}$		1	quarkonia
jet,$E_T = 50$		10^{-3}	Jets in matter
Hadrons with $A > 10$			Exotica: $Z/A \ll 1$

Table 2: Rough estimates (and some measurements in boldface) of the number of particles with $-0.5 < y < 0.5$ in an average central Pb+Pb collision and associated phenomena.

As an example of effects one can observe [8], Fig. 5 shows the transverse momentum slope parameter T obtained from measured p_T-distributions by the fit $dN/dp_T^2 \sim \exp(-\sqrt{p_T^2+m^2}/T)$ for $m = m_\pi, m_K, m_p$ and for various initial states. If there is flow with velocity $v_{\rm flow}$, particles of all masses are carried by it and they all obtain a momentum $p = mv_{\rm flow}$ which increases with increasing mass. This is precisely what one observes: the flow develops in large systems and slope parameter T grows rapidly with mass while no flow effect is observed in p+p.

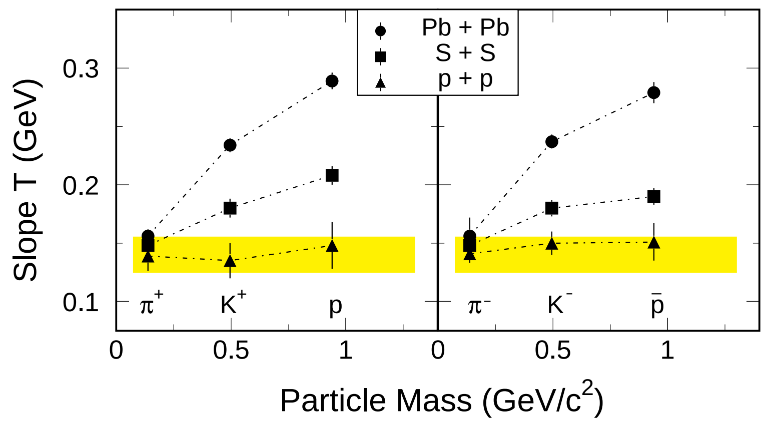

Figure 5: The slope parameter T of dN/dp_T^2 measured by the NA44 collaboration at the CERN SPS at $\sqrt{s}$=17 GeV.

"Baryon stopping" or the fate of the incident baryon number $B = 2 \cdot 208$ is also an interesting problem. What is the amount of net baryon number at $y = 0$ or how far beyond the nuclear matter density $n_0 = 0.17/\text{fm}^3$ can one compress the matter? Some people are namely interested in studying the effects of net baryon density rather than temperature and it may well be that the maximal values of this are reached at intermediate energies.

Two very well studied signals have an astronomical analogy:

Stellar sizes can in astronomy be measured with HBT (Hanbury-Brown–Twiss) interferometry: photons emitted incoherently from various portions of the star can interfere constructively if they are sufficiently close in momentum space. When applied to a heavy ion reaction one look at $\pi\pi$-correlations and there momentum dependence. Since the sizes one expects to see are of the order of 10 fm, the relevant momentum differences are of the order of $1/10$ fm $= 20$ MeV. Great accuracy is thus needed, but the main problem is that while a star is stationary, one now is studying an extremely transient relativistically moving system. The analysis thus is essentially more complicated, but one has now learnt to do this [7].

During the previous century astronomers noticed how the spectra of stars depended on their colour. For blue stars certain spectral lines disappeared. One now knows this is due to the fact that when the star is very hot (blue) atoms are ionised and are not there to cause the spectral line. In heavy ion physics the analogy is J/ψ suppression: this resonance (or its excited states) should not appear in quark-gluon plasma phase. A great boost to the image of heavy ion particle physics has been given by the recent observation [9] of this effect, shown in Fig. 6.

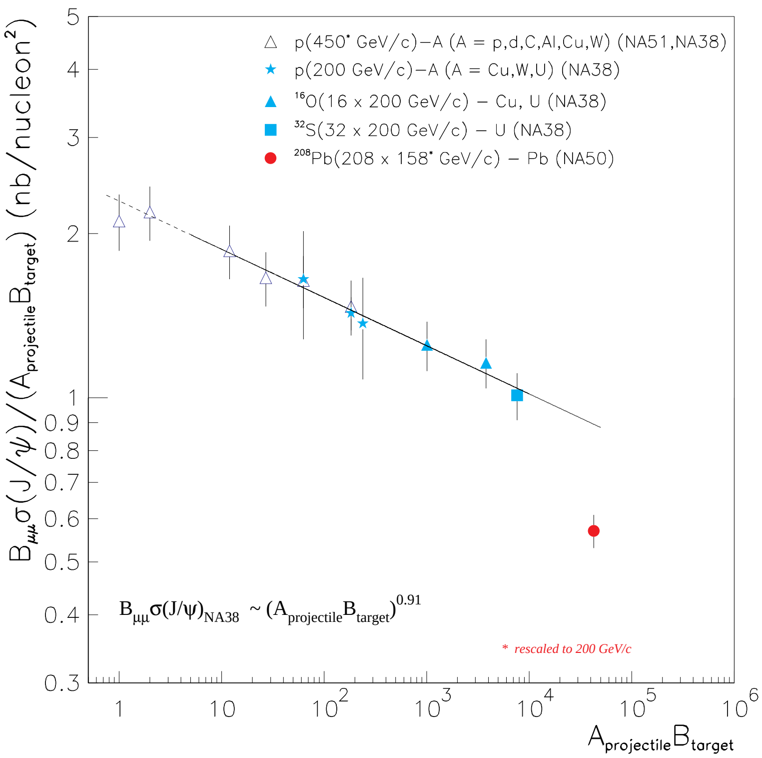

Figure 6: The J/ψ production cross section in $A+B$ collisions divided by AB and plotted versus AB. The last point for Pb+Pb is the remarkable one!

Another suggestive and promising idea is based on the fact that the widths of the e^+e^- decays of ρ, $(\Gamma_\rho^{-1} = (149\text{MeV})^{-1} = 1.3$ fm), ω, $(\Gamma_\omega^{-1} = 23$ fm) and ϕ $(\Gamma_\phi^{-1} = 45$ fm) are such that ρ decays inside and the others outside. Maybe the hot medium affects ρ, ω, ϕ so that their effective masses change? One can now study this by observing the decays $\to e^+e^-, \mu^+\mu^-$, which get out of the interior. A shift or change of shape of the ρ peak is now evidence of medium effects. Again, interesting hints of this has been observed [10].

5. ONE RESULT FROM FIRST PRINCIPLES: EQUATION OF STATE

In the above the rather limited predictability of heavy ion phenomena has been repeatedly emphasised. However, there is one very important quantity which, in principle and also almost in practice can be computed from first principles: the equation of state. This assumes that the system is infinitely large and lives infinitely long, which is certainly not the case with the objects one is experimentally studying. In statistical mechanics all the thermodynamics follows from computing the partition function

$$Z = \text{Tr}e^{-H/T} = \sum_{\text{states}} e^{-E_n/T} = e^{p(T)V/T}.$$

In field theory this can be symbolically be written in the form

$$e^{p(T)V/T} = \int \mathcal{D}\phi(\tau, \mathbf{x})\, e^{-S(\phi)},$$

where ϕ symbolises all the fields in the problem (the gluons A_μ^a, quarks ψ_i, etc.) in imaginary time $\tau = it$ and the action is

$$S = \int_0^{1/T} d\tau \int d^3x \mathcal{L}(\phi(\tau, \mathbf{x})).$$

Note that T only appears in the upper limit of the τ integration in S.

The problem has now been reformulated as an evaluation of a functional integral, which can be carried out by latticising the problem and feeding it into a computer. Much work has been devoted to this problem since about 1982, but the answer for QCD with physical quark masses is still unknown. For unphysical infinite quark masses a first order transition is obtained. However, one has the feeling that the final answer for QCD is within controllable reach, one knows what one needs in computing power and expects this to be available in a year or two. For the electroweak case the problem is essentially solved.

6. EARLY UNIVERSE AND HEAVY ION EXPERIMENTS

LEP and LHC have been and are often motivated by saying that "they reveal the conditions in the early universe".

This is a half truth, like saying that "one can study superconductivity observing single atoms". The basic laws (like those which one is studying with LEP and LHC) are quantum mechanics and electromagnetism and follow from experiments on single atoms, but for the phenomenon itself it is essential that the system is an extended one with interactions with the ionic lattice.

Atomic physics is necessary but not sufficient: the essence of the phenomenon is in collective interactions of the constituents of the system.

The only experiments which even remotely can be said to "reveal the conditions in the early universe" are actually the Pb+Pb collision experiments.

Even here scales differ by a huge factor, by $M_{\rm Pl}/T_c \approx 10^{19}$. The reason is that a new scale, the gravitational constant $G = 1/M_{\rm pl}^2$, has entered. Thus at $T = 150$ MeV the relevant distance scale is the horizon distance ≈ 10 km and the corresponding time $\approx 10\mu$s. Similarly, the expansion rate $dT/(Tdt)$ is $\sim 10^{19}$ slower than in Pb+Pb.

7. CONCLUSIONS

- Particle physics with heavy ion beams aims at studying condensed QCD matter in its two phases, the high T quark-gluon plasma phase and the low T hadron gas phase and the phase transition in between.
- The physics is dominantly nonperturbative and the predictive power of theory is very limited. Precise predictions can be made only for the equation of state. Many different experimental observables have to be studied and correlated.
- Very promising results have in 1995-6 been obtained from measurements of Pb+Pb at 158 GeV/c, there are unmistakable hints of collective behaviour and of the quark-gluon plasma phase.
- The discovery potential will be further greatly increased when going from SPS ($\sqrt{s}$=20) to RHIC ($\sqrt{s}$=200) and finally to LHC-ALICE ($\sqrt{s}$=5500 GeV).

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